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Note Added to  
“Baryon Asymmetry of the Universe  
in the Standard Model”<sup>1</sup>

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**Abstract:** Recent papers by Gavela et al and Huet et al claim to have shown that inclusion of higher order interactions between quasiparticles dramatically decreases the baryon asymmetry of the universe which can arise in the Minimal Standard Model. These papers employ an inconsistent calculational scheme which, for instance, violates unitarity. We argue that their method cannot be considered as reliable, and thus their conclusions cannot be considered as justified.

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In our paper we estimated the baryonic asymmetry of the universe which was produced by MSM interactions during the ew phase transition, through CP violation in the reflection of quasiparticles from the bubble wall. The next corrections to our result (down by a factor  $\alpha_s$ ) involve processes in which reflection as well as scattering from other particles in the plasma (which themselves may reflect from the wall) are occurring simultaneously. We emphasized (section 10.4) the importance of understanding these higher order effects before one could have confidence in the conclusion that the MSM may account for the observed bau. However developing a formalism for correctly including these higher order processes is quite non-trivial and requires construction of a kinetic theory (or, more generally, real time Green's function approach) describing processes near the domain wall.

Recently, papers have appeared[1, 2] claiming that the result of including these effects is to drastically diminish the bau produced in the MSM. In lieu of working in a consistent field-theoretic formalism, these papers adopt the ad hoc procedure of modifying the single-particle Dirac equation to include a finite lifetime for the quasiparticle. One manifestation of the inconsistency of this procedure is that it violates unitarity, making physical predictions ill-defined. The usual kinetic equation [3] uses matrix elements computed from a unitary S matrix, and dissipative processes emerge through solution of the kinetic equation rather than by any modification of quantum mechanics. We expect the same will be true in the kinetic theory approach applied to this problem.

Another deficiency of the treatment of refs. [1, 2] is that it excludes *by assumption* the strong interaction phase relations which order-by-order can compensate the loss of total reflection which is introduced by their ad hoc inclusion of an imaginary part of the fermionic Green's function into the Dirac equation or ad hoc assumptions about decoherence[1, 2]. As long as total reflection is the only source of the CP conserving phase which must be present in order to produce a CP violating difference in rates, diminishing

total reflection necessarily diminishes the asymmetry. However this need not be the case in a complete calculation, consistently including particle interactions, since ordinary strong interaction phase shifts can serve the function of providing a CP conserving phase.

To see that higher order scattering from gluons need not dramatically wash out the effect, consider more microscopically what happens when a quasi-particle scatters from a gluon while interacting with the wall. Recall that the CP-violation occurs because of the quantum mechanical sum over the different paths in flavor space that the quasi-particle can take. We discussed in section 8 how this occurs in our approximation, in which we included forward scattering of the quarks with the charged W's and Higgs of the heat bath by using the one-loop quasiparticle propagator. It is even more transparent when one considers the leading multi-particle process:

$$q_L^i + \{W, H\} + wall \rightarrow q_R^j + \{W, H\} + wall. \quad (1)$$

In this case, the interference arises from the coherent sum on amplitudes for the intermediate state to contain a quark of flavor  $k$ . How does the interference between these paths differ when there is an additional interaction with a gluon somewhere in the process? Some phase shift of a random nature will be introduced into both the CP conserving and violating parts, but it is the the same for both, and is the same for each flavor. Thus the only change in the result is that the particular quark under consideration contributes with an effectively different energy than it would have done without the gluonic scattering. However the contributions of different energies do not cancel, because the reflection phase shift is always between 0 and  $\pi$  as noted in section 8, so this is not a significant effect.

What does matter and can modify the result, are processes in which the quantum coherence in flavor space is lost due to flavor changing interactions such as  $q + gluon \rightarrow q' + Higgs$ . The time scale associated with these interactions is  $\tau_{coh} \sim (g_s^2 f^2 T)^{-1}$  with  $f$  being the Yukawa coupling constant.

This is to be compared to the typical flavor oscillation time due to forward scattering on the Higgs particles,  $\tau_{osc} \sim (p_i - p_j)^{-1} \sim g_s/(f^2 T)$ . Since the coherence time is parametrically larger than the time required for the flavor oscillation which gives rise to the CP violating interference, i.e.,  $\tau_{coh} \sim g_s^{-3} \tau_{osc}$ , it is consistent not to take into account these effects. They make a higher order correction to the leading result, corresponding to additional real Higgs or  $W^\pm$ 's in the initial or final states.

In the absence of employing a legitimate, well-defined approximation scheme, reliable results are not assured. Thus the claims of refs. [1, 2] are not justified by the work reported in them. Generation of the observed  $b$  by MSM physics must be considered to be an open possibility until the necessary first-principles methods have been developed and applied to the problem.

## References

- [1] B. Gavela, P. Hernandez, J. Orloff, and O. Pene. Technical Report CERN-TH.7081/93, 1993.
- [2] P. Huet and E. Sather. Technical Report SLAC-PUB-6479, 1994.
- [3] E. A. Uehling and G. E. Uhlenbeck. *Phys. Rev.*, 43:552, 1933.